WorldWide ElectroActive Polymers

WW EAP

(Artificial Muscles) Newsletter

June 1999 WW-EAP Newsletter Vol. 1, No. 1

http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm

FROM THE EDITOR

Yoseph Bar-Cohen, JPL yosi@jpl.nasa.gov

For many years, electroactive polymers (EAP) received relatively little attention due to the small number of available materials as well as their limited actuation capability. The recent emergence of EAP materials with large displacement response changed the paradigm about these materials and their potential capability. Their main attractive characteristic is their operation similarity to biological muscles particularly their resilience and ability to induce large displacements. Unique robotic components and miniature devices are being explored, where EAP serve as actuators to enable new technologies. In recognition of the need for international cooperation among the developers, users and potential sponsors, an SPIE Conference was organized for the first time on March 1-2, 1999, at Newport Beach, California. This conference has been the largest ever on this topic, it marked an important milestone for the field and it turned the spotlight onto these emerging materials and their potential. To bring closer the EAP community worldwide this WW-EAP Newsletter was initiated and it is issued for the first time.

A challenge was posed to the EAP science and engineering community to develop a robotic hand that is actuated by EAP and win against human in an arm wrestling match. Progress towards this goal will lead to great benefits particularly in the medical area including effective prosthetics. Decades from now, EAP may be used to replace damaged human muscles, leading to "bionic human" of the future. My hope is to see someday a handicapped person

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jogging to the grocery store using this technology.

GENERAL NEWS

To enhance the international cooperation among those who are interested in the field of EAP two forums of communication were initiated: WW-EAP Newsletter and the EAP Actuators Worldwide Website. Also, two annual conferences on EAP are now in place: SPIE (in March)- covering actuators and devices; and MRS (in November) - covering material science.

WW-EAP NEWSLETTER

This WW-EAP Newsletter was formed to provide a timely update and a technical communication platform. Efforts are made to solicit input worldwide from experts who are developing new mechanically active polymer materials and processes, improving the understanding of these materials that their electro-mechanical/chemical characteristics, exploring new applications, investigating relation of EAP and biology as well as others. The input is the format of an abstract with a contact name and e-mail address.

EAP Actuators Worldwide Website

Internet is one of the leading forms of communication that rapidly took over many other methods that were the standard forums. A website was established containing hotlinks to the various research organizations that are active in the field of EAP: http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm

SPIE Conference

In recognition of the need for international cooperation among the developers, users and potential sponsors, an SPIE Conference was organized for the first time on March 1-2, 1999, at Newport Beach, California. This has been the largest conference ever held on the topic of EAP and involved about 150 scientist and engineers. Besides the technical exchange, one of the major achievements has been the turning of the spotlight onto these emerging materials and their potential.

About 50 papers and posters were presented at the conference in support of this emerging technology area. The conference was well attended by leading world experts in the field and many individuals from the academia, research institutes, industry, and government agencies in the USA and overseas who are interested in the technology. The conference was followed by a session entitled "EAP in Action" which was intended to give the participants a hand-on experience with the various state-of-the-art EAP materials as well as seeing videos that show EAP materials in action. The proceedings of the conference was issued at the beginning of June and it is now available from SPIE.

The next SPIE conference on EAP will be held on March 5-6, 2000 and the abstracts are due on 9 August 1999. This conference will be held as part of the 7th International SPIE Symposium on Smart Structures and Materials. For more information please see:
http://www.spie.org/web/meetings/calls/ss00/ss04.html

MRS Meeting

To address issues related to material science of electroactive polymers a Symposium FF, was initiated by Qiming Zhang, Penn State and it is being organized as part of the MRS Fall 1999 Meeting. This meeting will be held in Boston, Massachusetts from November 29 to December 3, 1999. The abstracts for this Meeting were due by June 21. Some of the topics that will be covered includes ferroelectric polymers, polymer composites, polymer gel, and thin polymer films, for applications in smart materials, actuators, transducers, and microelectronics. More information about this meeting is available on:
http://www.mrs.org/meetings/fall99/

AUSTRALIA

WOLLONGONG UNIVERSITY

Advances in Polymer Actuators

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The configuration of "solid" state polymer actuators under investigation in our laboratories is shown in Figure 1. The performance of such devices has recently been described in the references listed below. Currently the work at

IPRI is focussed on the optimization of these devices. This has involved the following studies.

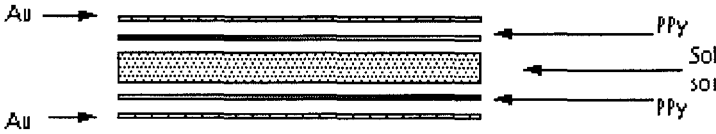

Figure 1 Solid state CEP device based on gold coated PPy.

(1) Studies into the electrochemical processes occurring with two polymer electrode actuators - It is important to understand that the conductivity of ICPs changes dramatically as they are oxidized and reduced. This works to advantage in a two-polymer electrode actuator. The increased resistance upon electrochemical reduction causes a potential drop that lowers the potential applied between the electrodes preventing over-oxidation of the other component of the device. Optimization of the potential difference enables repetitive stimulation of the all polymer actuator to be carried out with no loss in performance. (Ssubmitted for publication in Journal of Synthetic Metals).

(2) Configuration of device -The performance of all polymer devices is limited by the diffusion of ions in/out of the polymer. This will be determined by composition of the active polymer electrodes as well as the solid polymer electrolyte (ion source/sink) and also by device configuration. We have also recently shown that the use of polymer coated PTFE fibres as the active electrode increases the force densities achievable by an order of magnitude compared with the use of simple conducting polymer films. (To appear in Journal of Synthetic Metals).

(3) New polymer actuator materials - In parallel studies in our laboratories we have developed synthesis protocols for a number of novel polythiophenes. These materials have excellent mechanical properties and importantly as far as polymer actuators are concerned have a wide electrochemical potential window.

(4) In other studies we continue our work into the use of novel solid polymer electrolytes. As the active (ICP) electrode materials are optimized then the performance (ionic conductivity, mechanical properties, environmental stability) of the SPE becomes the limiting factor in determining the performance efficiency of all polymer actuator devices. Our studies involve a range of solid polymer electrolyte (e.g., polyacrylonitrile, Kynar, polyvinyl alcohol) and hydrogel (e.g., polyacrylamide) ion source/sinks. Figure 2 shows the CV obtained from one such device that utilizes a polyacrylonitrile based solid polymer electrolyte.

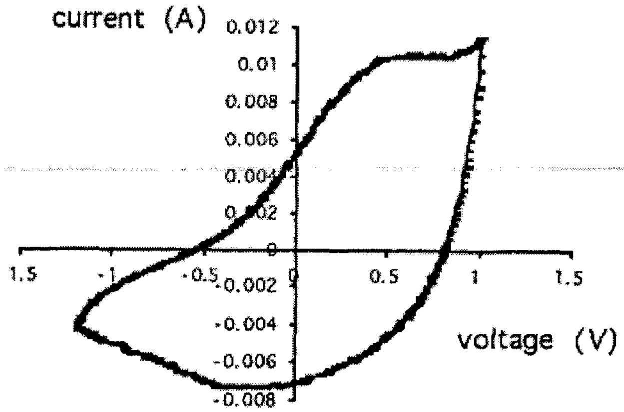

Figure 2: Cyclic voltammogram of PPy-SPE-PPy sandwich against a Ag/AgCl reference at 10 mV/sec. PPy/ClO4/pTS films as working and counter electrodes, and PAN/PC/EC/NaClO4 as SPE.

References:

Lewis, T.; Spinks, G.; Wallace, G.; De Rossi, D.; Pachetti, M. *Polymer Preprints*, 38(2),1997, 520

Lewis, T.; Moulton, S.; Spinks, G.; Wallace, G, *Synthetic Metals*, 85 (1997) 1419

Lewis, T.;Kane-Maguire, L.; Hutchison, A.; Spinks, G.; Wallace, G, *Synthetic Metals* (In Press).

JAPAN

HOKKAIDO UNIVERSITY

Chemical Motor Driven by Immersing Polymer Gel in Organic Solvent

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and Jianping Gong gong@sci.hokudai.ac.jp

Prof. Yoshihito Osada and his research team of Division of Biological Sciences, Graduate School of Science, Hokkaido University, have developed a chemical motor that obtains its rotary force by immersing a polymer gel in an organic solvent such as alcohol (Figure 3). When a gel with absorbed organic solvent is floated on water, the absorbed organic solvent is discharged and becomes active immediately and continuously.

This phenomenon is utilized, and by feeding the gel continuously with the organic solvent, the chemical motor continues to revolve infinitely. The research team observes that there is a great possibility of utilizing this chemical motor as a pollution-free "fuel battery" that uses alcohol for regeneration as the energy source.

The research team opened small grooved holes on both terminals of the rotor to accommodate the polymer gel, packed polystearile acrylate (PSA) gel there, followed with the addition of alcohol. The grooved holes at both terminals are positioned at opposite directions, so when the rotor is floated on water, it starts revolving with the stator as its axis. The rotary speed of this chemical motor is changed radically with the motor's mass, and with an experimentally fabricated motor of 25-mg, a maximum speed of 400-rpm was attained. Without supplementation of organic solvent, the motor revolved for a maximum of three hours. In an experiment in which a generator was connected to convert the chemical motor's rotary energy into electric energy, an instantaneous electromotive force of maximum 15-millivolts and power of 2.1 x 10^{-7} joules were obtained. This corroborated that chemical energy can be converted directly into motional energy, and then further into electric energy.

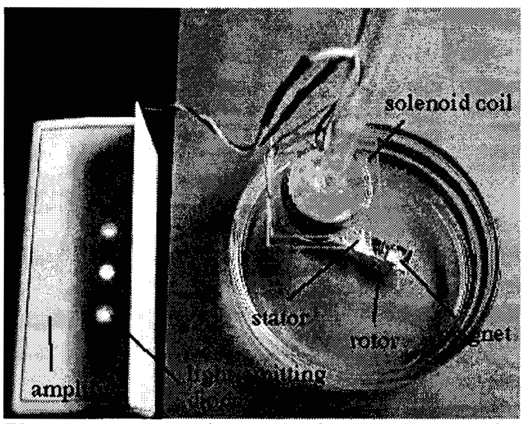

Figure 3: Experiment using generator in organic solvent impregnated with gel.

OSAKA NATIONAL RESEARCH INSTITUTE

Electroactive Tubular Actuator

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The joint research group of Osaka National Research Institute and Japan Chemical Innovation Institute has developed an electroactive bending tube made of an ion-exchange polymer tube and gold electrodes (Figure 4). The gold electrode plated on the outer surface of the tube was divided in four strips in parallel with the axis. The tubular actuator (0.6 mm in outer diameter and 15 mm in length) bends over 90 degree for all directions by 3 V electric stimuli between the electrode pairs. It works as the tip of an active micro catheter for the intravascular surgery.

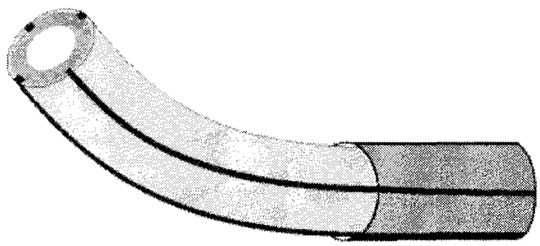

Figure 4: Active Catheter guide using the bending EAP type IPMC.

SHINSHU UNIVERSITY

Polymer Gel Generating Bending and Crawling Motion

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Nonionic polymer gel swollen with dielectric solvent shows tremendous action in air by applying dc electric field (Figure 5). Poly(vinyl alcohol) gel swollen with dimethyl sulfoxide showed swift bending and crawling motion by the electric field. The gel used has the dimension of 10-mm in length, 3-mm in width, and 2-mm in thickness. Bending angle of 90 degree was attained within 60-ms when the field was applied on both surfaces of the gel. The gel stripe could crawl on the array of the stripe electrodes. These phenomena were explained by charge injection into the gel and the flow of the solvated charge that can induce asymmetric pressure distribution in the gel. This idea can be applied to the conventional polymer materials. The motion is not only extreme in magnitude but far quicker than any other electroactive polymer gels reported at this moment.

(Reference: SPIE, Vol. 3669, 209-217 (1999))

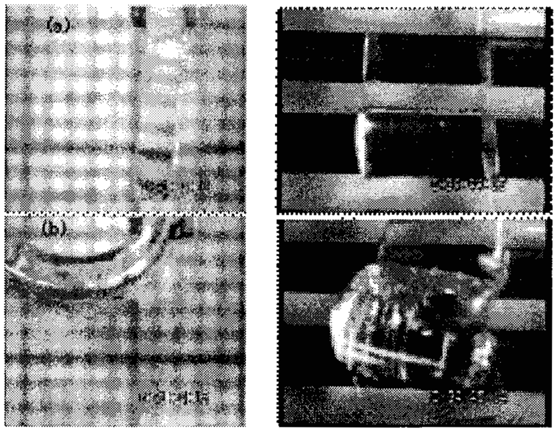

Figure 5: Polymer gel bending (left) and crawling (right).

TAIWAN

INDUSTRIAL TECHNOLOGY RESEARCH INST.

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For many years, the main focus of the Division of Composite Materials of Materials Research Laboratories (MRL), at the Industrial Technology Research Institute (ITRI), has been on industrial application of polymeric materials. This division accumulated extensive data and experience on materials selection, CAE simulation, structural design and product development. Recently, the focus of the efforts was shifted to include seeking applications for EAP actuators that can meet air flow needs of computer/ communication/ consumer-electronic (3C) industries. This effort involves structural analysis and development of new products. The MRL Division is receiving technical assistance and data from Hokkaido University and University of Pisa including information about EAP materials density, modulus, strain, electrochemical strain coefficient, etc.

USA

ALLIED SIGNAL

Carbon Nanotube Optical Fiber Switch

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Recently, carbon Nanotubes have been demonstrated as effective electroactive polymer materials. A tube with constructed with optical fiber and was made to move in differing amounts in two independent directions (indicated by arrows) depending upon the voltages applied to the actuators, thereby switching between optical fibers. The device diameter is about that of a human hair (Figure 6 and 7).

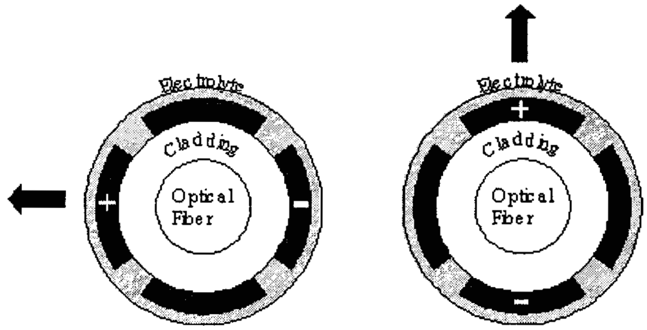

Figure 6: Nanotubes activated in two orthogonal directions

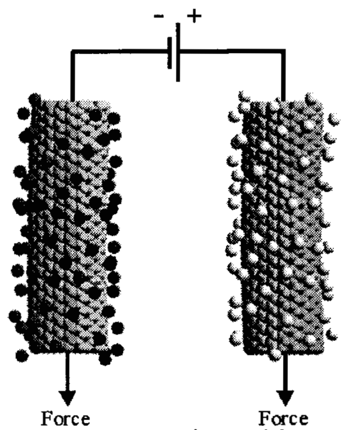

Figure 7: Nanotubes activated in two orthogonal directions

JPL

EAP Used to Develop a Dust-Wiper for MUSES-CN Mission to an Asteroid

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A team consisting of S. Leary, JPL; J. Harrison, J. Smith and J. Su, NASA-LaRC; T. Knowles, ESLI; in cooperation with K. Oguro, Osaka National Research Institute, Japan, and S. Tadokoro, Kobe University, Japan, is developing a dust wiper using a bending EAP actuator for the NASA/NASDA MUSES-CN mission. This dust-wiper is being developed for the infrared camera window of the mission's Nanorover (Figure 8). This joint NASA and the Japanese space agency mission, is scheduled to be launch from Kagoshima, Japan, in January 2002, to explore the surface of a small near-Earth asteroid.

The team is testing the use of the highly effective ion-exchange membrane metallic composites (IPMC) that is made of perfluorocarboxylate-gold composite with the two types of cations tetra-n-butylammonium and lithium. Under less than 3-V, these IPMC materials are capable of bending beyond a complete loop. A unique <100-mg blade with a fiberglass brush was developed by ESLI (San Diego, CA) and is powered with a high voltage to repel dust augmenting the brushing mechanism provided by the blade.

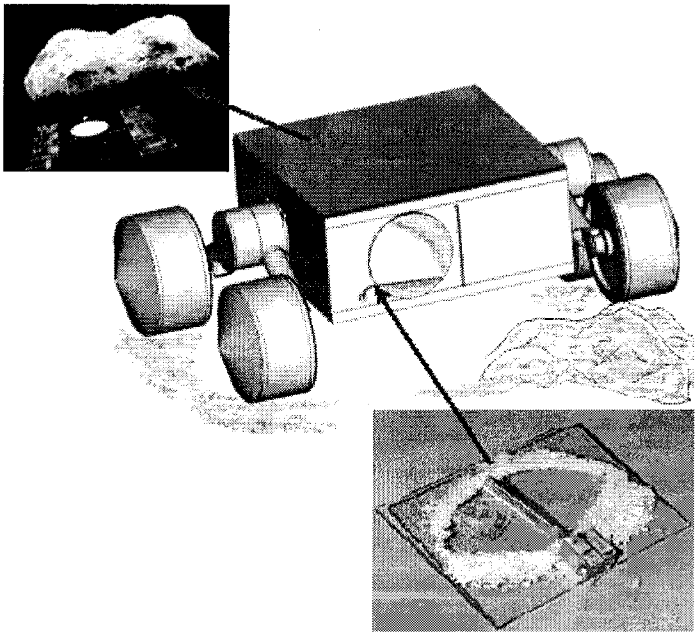

Figure 8: Schematic view of the EAP dust wiper on the MUSES-CN's Nanorover (right) and a photographic view of a prototype EAP wiper (left).

Generally, space applications are the most demanding in terms of operating conditions, robustness and durability, and the team is jointly addressing the associated challenges. Several issues that are critical to the operation of IPMC are examined including operation in vacuum and low temperatures, as well as the effect of the electromechanical characteristic of IPMC on its actuation capability. The use of highly effective IPMC materials, mechanical modeling, unique elements and protective coating were introduced by the team to assure a high probability of success for this IPMC actuated dust-wiper.

Cold Hibernated Elastic Memory (CHEM) Self-Deployable Structures

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The concept called "cold hibernated elastic memory" (CHEM) utilizes polyurethane-based shape memory polymers (SMP) in open cellular (foam) structures. The CHEM structures are self-deployable and are using the foam's elastic recovery plus their shape memory to erect a structure. In practice, the CHEM foams are compacted to small volume above their softening (glass transition) temperature Tg. They may then be stored below their Tg without constraint. Heating to a temperature above their Tg restores their original shape. The advantage of this exciting new technology is that structures when compressed and stored below Tg, are a small fraction of their original size and are lightweight. Examples of stowed and deployed CHEM structures are shown in Figure 9.

The attractiveness of the CHEM structure is the wide range of Tg resulting in a variety of potential space and commercial applications. In commercial application the CHEM concept could be applied to shelters, hangars, camping tents, rafts or outdoor furniture to mention just a few. The CHEM parts can be transported and stored in small packages then expanded by heating at the outdoor site. After expansion, CHEM parts will be allowed to cool to ambient temperature below their Tg, so that they would become rigid as needed for use. CHEM foam materials are under development by the Jet Propulsion Laboratory (JPL) and Mitsubishi Heavy Industries (MHI). The CHEM structure technology was designed to be developed in 3 phases: Phase 1: Proof-of-CHEM Concept (already completed), Phase 2: Characterization and sub-scale CHEM application development (present activities) and Phase 3: Full-scale CHEM application technology ground validation (future activities).

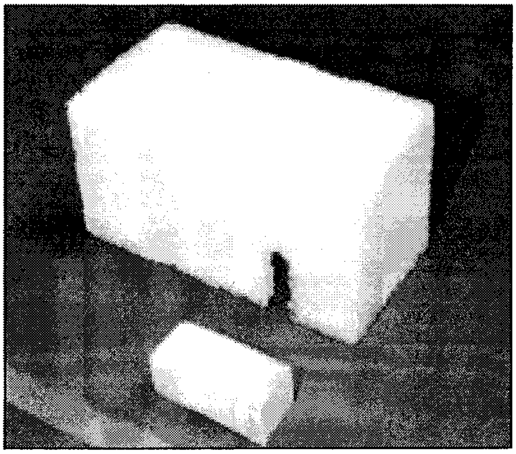

Figure 9: Stowed and deployed CHEM structures.

NASA-LaRC

Electrostrictive Graft Elastomers and Applications

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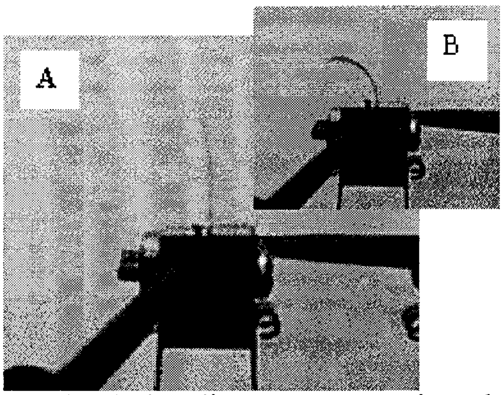

Figure 10: A bending actuator using the new electroactive graft elastomer (A) With no applied voltage and (B) under applied voltage.

Recently, a new class of electro-mechanically active polymers was developed at NASA-LaRC under the JPL's task LoMMAs. The polymers are grafted elastomers that offer high strain under an applied electric field. Due to its high mechanical modulus, these elastomers offer a higher strain energy density than the previously reported result for such electrostrictive polymers as polyurethane. The dielectric, mechanical and electromechanical properties of this new electrostrictive elastomer are currently being studied as a function of temperature and frequency. Also investigated are the microstructure and mechanism of electrostriction in this grafted elastomer. X-ray diffraction and differential scanning calorimeter are used in this investigation. This new EAP demonstrated high actuation strain and high mechanical energy density combined with its designable molecular composition as well as excellent processability. Example of the bending response of a grafted polymer configured as a bimorph is shown in Figure 10.

PENN STATE UNIVERSITY

Electroactive Polymers with High Electrostrictive Strain and Elastic Power Density

Qiming Zhang, qxz1@psu.edu

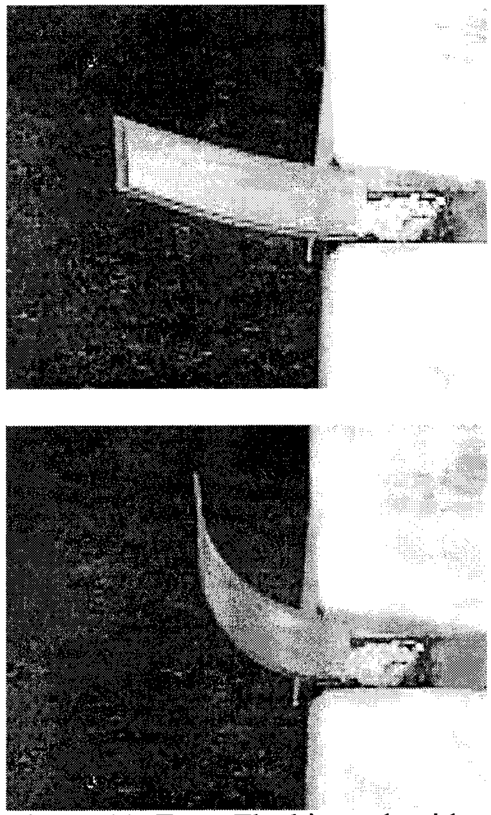

Figure 11: Top - The bimorph with no voltage applied to it. Bottom - The same bimorph after the voltage was turned on.

In many polymeric materials, a structure or conformational transformation is often associated with large dimensional change. However, it is still a challenge to make use of these transformations and electrically induce the transformation without much hysteresis for practical actuator applications. Recently, we found that in Poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE)) copolymers, a giant electrostriction (strain >5%) can be induced when the polymer is treated with a proper high energy electron irradiation (Figure 11). Furthermore, the polymer has a high elastic modulus (~1 GPa) and the field induced strain can operate at frequencies higher than 100 kHz, which result in a very high elastic power density compared with any electroactive polymers reported.

The new polymer actuators can be operated in air, vacuum, or water and in a wide temperature range. Extensive structural investigations indicate that the high electron irradiation breaks up the coherence polarization domain and transforms the polymer into a nanomaterial consisting of local nanopolar regions in a nonpolar matrix. It is the electric field induced change between non-polar and polar regions that is responsible for the giant electrostriction observed in this polymer.

SDSM&T AND MSU

Active Polymers: Properties and Applications

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Current research interests concern the use of active polymers for space applications. MSU is investigating polyvinylidene fluoride (PVDF) for active vibration control in microgravity environments. The polymer can be characterized as a light, compliant material that exhibits considerable dielectric strength, high sensitivity to mechanical loads and stable piezoelectric properties in diverse chemical environments.

Creep tests of PVDF thin films under room temperature conditions demonstrate that linear viscoelastic theory based on Boltzmann's superposition principle accurately represents the time-dependent response of PVDF provided that the applied stresses remain below certain limits. Beyond these limits, creep properties of PVDF must be characterized by a nonlinear viscoelastic constitutive model (Figure 12).

The Compliant Structures Laboratory at SDSM&T has shown in simulations that manipulating the boundary (rim) of an inflatable membrane reflector reduced the figure error in the inflated profile. An inflated membrane reflector was simulated using the nonlinear FEM code ABAQUS. PVDF actuators were simulated to apply radial boundary displacements (Figure 12). Table 1 shows the rms surface error for two cases of uniform radial boundary displacement after inflation: 2.54 mm and 5.08 mm, respectively. It is seen that the surface error is significantly reduced by the boundary manipulation.

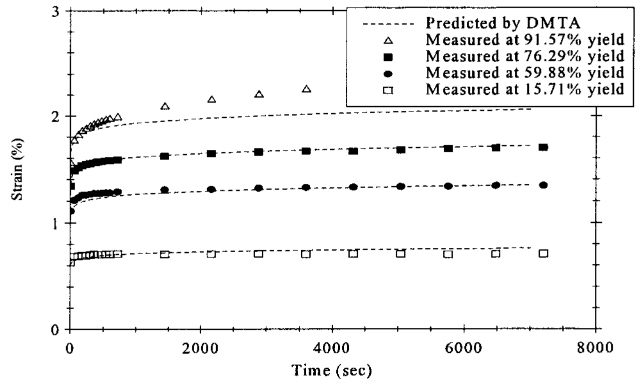

Figure 12: Creep of PVDF (material direction 1).

Table 1. Comparison of precision metrics, with and without uniform radial boundary displacements (F=1.04).

Boundary displacement	Pressure	1/2 aperture	w0	RMS surface Error	% improvement
mm	kPa	mm	mm	mm	
0.0	5.17	533	64.0	1.31	--
2.54	7.72	536	64.5	1.12	14.5
5.08	10.2	538	64.8	0.886	32.4

SRI INTERNATIONAL

Electrostatically actuated EAP is showing large actuation strain

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Roy Kornbluh, roy.kornbluh@sri.com

For the past seven years, SRI International has been developing an actuator technology based on the deformation of soft-rubbery dielectric materials under the influence of high electric fields. A key feature of this technology is the use of highly compliant electrodes that allow thin polymer films to expand in area as they compress in thickness. Initial work was focused on the development of artificial muscle microactuators as part of Japan's Micromachine Program, sponsored by MITI. This effort is led by Dr. Ron Pelrine. The research team includes individuals working in the areas of physical electronics, polymer chemistry and mechanical and electrical engineering.

Silicone rubber materials (based on polydimethyl siloxane) have reliably shown the greatest strain deformation. A variety of other rubbery dielectric polymers have also shown large strains. Recently, SRI has been able to reproducibly achieve more than 100% strain in a planar direction with a stretched silicone rubber film (see Figure 13). The specific elastic energy of such materials is comparable to the best field-actuated materials, including single-crystal piezoelectrics. The good electromechanical response of these materials, as well as other characteristics such as good environmental tolerance and long-term durability, suggest a wide-range of possible applications. SRI has made actuators in configurations such as bending beams (unimorphs and bimorphs), linear extenders, diaphragms, rolls, tubes, stacks as well as some novel configurations. Rotary and linear motors, that rectify the oscillation of linear actuator elements, have also been demonstrated.

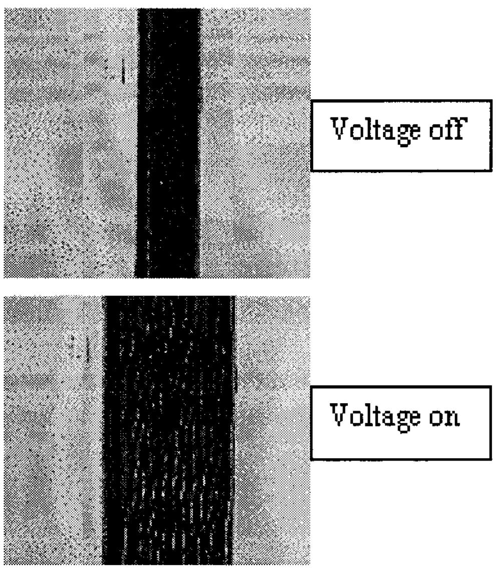

Figure 13: Stretched Silicone-rubber film with carbon-grease electrodes (dark area) undergoing 117% strain in the transverse direction.

These elastomeric polymer transducers present many unique challenges in design, fabrication and integration with high-voltage electronic drivers that may ultimately affect their suitability for specific applications. Applications that are under active investigation include acoustic actuators for smart skins and low profile speakers, microactuators for pumps and valves and optics, artificial muscle actuators for biomorphic walking, flying and serpentine robots. SRI has also recently begun investigating these materials, not only as actuators, but also as electric power generators for converting human motion and other mechanical work into electricity.

UNIVERSITY OF CALIF., SAN DIEGO (UCSD)

Electromechanical Response of Ionic Polymer-Metal Composites

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An ionic polymer-metal composite (IPMC) consisting of a thin Nafion sheet, platinum plated on both faces, undergoes large bending motion when an electric field is applied across its thickness. Conversely, a voltage is produced across its faces when it is suddenly bent. A micromechanical model is developed which accounts for the coupled ion transport, electric field, and elastic deformation to predict the response of the IPMC, qualitatively and quantitatively. First the basic three-dimensional coupled field equations are presented, and then the results are applied to predict the response of a thin sheet of an IPMC. Central to our theory is the recognition that the interaction between an imbalanced charge density and the backbone polymer can be presented by an eigenstress field. The constitutive parameter connecting the eigenstress to the charge density is calculated directly using a simple microstructural model for Nafion. The results are applied to predict the response of samples of IPMC, and good correlation with experimental data is obtained. Experiments show that the voltage induced by a sudden imposition of a curvature, is two orders of magnitude less than that required to produce the same curvature. The theory accurately predicts this result. The theory also shows the relative effects of different counter ions, e.g., sodium versus lithium, on the response of the composite to an applied voltage or a curvature.

Skeletal Muscle is a Biological Example of a Linear Electro-Active Actuator

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Skeletal muscle represents a classic biological example of a structure-function relationship. Muscle anatomy demonstrates molecular motion on the order of nm distances that is converted to macroscopic movements in skeletal muscle. Muscle anatomy provides a structural basis for understanding the basic mechanical properties of skeletal muscle—namely, the length-tension relationship and the force-velocity relationships. The length-tension relationship illustrates that muscle force generation is extremely length dependent due to the interdigitation of the contractile filaments. The force-velocity relationship is characterized by a rapid force drop in muscle with increasing shortening velocity and a rapid rise in force when muscles are forced to lengthen. Finally, muscle architecture—the number and arrangement of muscle fibers—has a profound effect on the magnitude of muscle force generated and the magnitude of muscle excursion. These concepts demonstrate the elegant manner in which muscle acts as a biologically regenerating linear motor. These concepts can be used in developing artificial muscles as well as in performing surgical reconstructive procedures with various donor muscles.

UNIVERSITY OF MICHIGAN, ANN ARBOR

Organic Polymer Light-Emitting Devices and Displays

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Through optimization of the organic polymer light-emitting device (OLED) structure and modification of polymer's chemical structure, we have fabricated the high-performance organic polymer light-emitting hetero-structure devices on both the glass and flexible plastic substrates. The OLEDs fabricated on the glass substrate showed a brightness of ~10,000 cd/m^2, external quantum efficiency of 3.8%, emission efficiency of 14.5 cd/A, and luminous efficiency of 2.26 lm/W. Using a unique charge-coupled device (CCD) calibration method developed in our group, we have obtained the spectral distribution of the luminance, photon emission of the organic light-emitting device.

Today we are trying to develop the active-matrix organic polymer light-emitting displays on both glass and plastic substrates. The active-matrix arrays are based on hydrogenated amorphous silicon thin-film transistor technology.

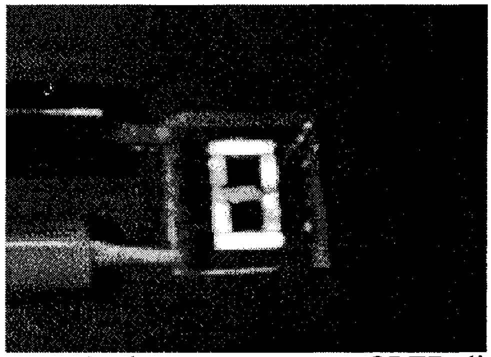

Figure 14: The seven-segment OLED display. (Photo taken in the ambient conditions under the regular room light.)

Reference:

Y. He, S. Gong, R. Hattori, and J. Kanicki, Appl. Phys. Lett., 74, 2265-2267, (1999).

Y. He, S. Gong, R. Hattori, and J. Kanicki, Proc. of Asia Display'98, 1095-1098, (1998).

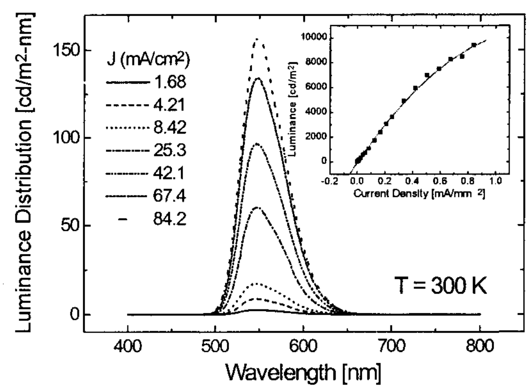

Figure 15: Spectral distribution of the OLED luminance under different operating current densities. The inset shows the OLED brightness versus injection current

UPCOMING EVENT

Sept. 20-23, 1999	4th Workshop on Multifunctional & Smart Polymer Systems, Dublin, Ireland, Celine.Healy@dcu.ie
Nov. 29 to Dec. 3 1999	MRS, Boston, MA, Website: http://www.mrs.org/meetings/fall99/cfp/symposia/ff.html
6-7 March, 2000	SPIE joint Smart Materials and Structures and NDE, Newport Beach, CA., Pat Wight patw@spie.org Website: http://www.spie.org/web/meetings/calls/ss00/ss04.html

WorldWide Electroactive Polymers (EAP) Newsletter

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